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# NOZZLE TESTS FOR SIMULATING HEAVY RAIN IN A WIND TUNNEL

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Tests were conducted with a vibrating tube nozzle system to assess the ability of the system to realistically simulate the natural heavy rain environment at wind tunnel airspeeds of 65 to 125 mph. The nozzle system was specifically designed to achieve the large droplet sizes (_2mm) that are characteristic of the heavy rain environment. The nozzle system also produced the appropriate total water volume to simulate rain rates from 25 mm/hr to over 500 mm/hr. The test results established the allowable velocity differential between the airstream and water velocity that resulted in large droplet formation. Velocity differentials exceeding the allowable or critical value resulted in the shattering of large drops into a spectrum of much smaller drops.

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# FOREWORD

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The work reported was conducted by the University of Dayton Research Institute with James Luers as Principal Investigator. Mr. Ira Fiscus was responsible for the engineering design work on the nozzle system and assisting in the data collection. The authors are indebted to Lt. William Crisler for his review of the document and to secretaries Jacki Aldrich and Gretchen Walther for their diligence in typing the manuscript.

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# SPRAY NOZZLE TEST FOR SIMULATING HEAVY RAIN IN A WIND TUNNEL

## INTRODUCTION

The UDRI Low Speed Environmental Wind Tunnel has been refurbished and upgraded to provide a means for simulating the effects of the natural heavy rain environment on moving airfoils, high lift devices, and sensors. The environmental wind/rain tunnel, with a 3' by 3' test section, provides a means of observing and measuring water droplet impacts on an object at air speeds up to 150 mph. Figure 1 shows a sketch of the wind/rain tunnel. The variable pitch axial vane fan is powered by a 255 hp Lycoming aircraft engine. Variation of the operating rpm of the engine and the pitch of the fan blades allows for airspeeds of 20 mph to 150 mph to be achieved in the test section. Approximately 6 feet forward of the test section, in front of the tunnel inlet, stands a vibrating tube nozzle system. Interchangeable nozzles consisting of from one to 8 tubes of a given tube diameter, with a length to diameter ratio of 50, permit the simulation of rain intensities from 10 to 1000 mm/hr in the test section. The nozzle can be raised or lowered from the center line of the tunnel to simulate droplets striking the model at various angles. The nozzle (see Figure 2) is attached by a moveable bearing to a rigid structure supported from the walls of the building. A second attachment point for the nozzle is to a bearing rigidly interacting with two shakers via force transmitting rods. The two rods, attached horizontally and vertically between the nozzle and uni-directional shakers, allow the nozzle to vibrate in two directions at variable frequencies. The frequency range for each shaker varies from 1 to 100 Hz with independent control for each. The stroke length of each shaker varies with frequency and load and cannot be controlled independently.

This report discusses results from tests that were made with the spray nozzle system, and assesses the ability of the

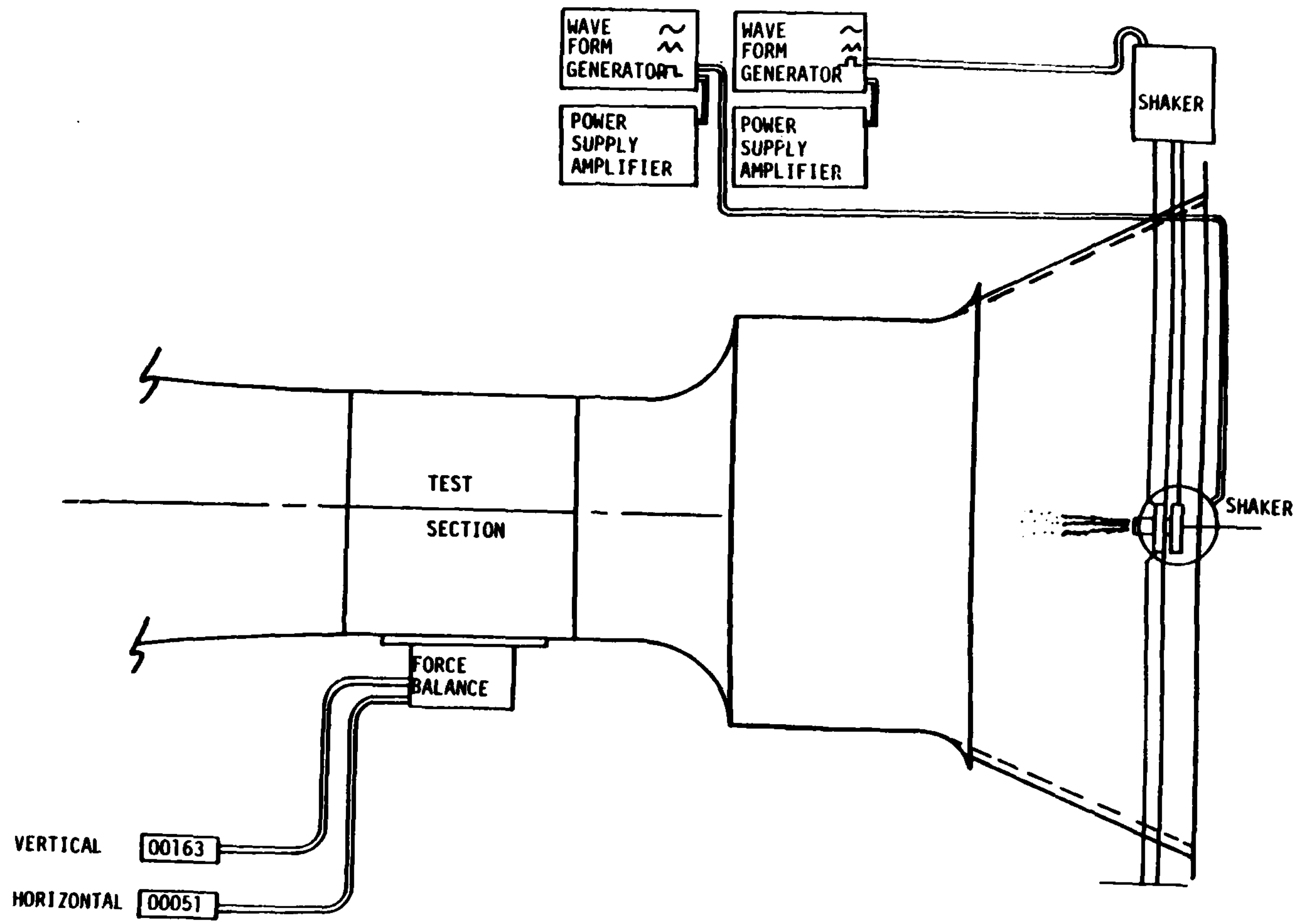


Figure 1. Sketch of Front Segment of Wind/Rain Tunnel.

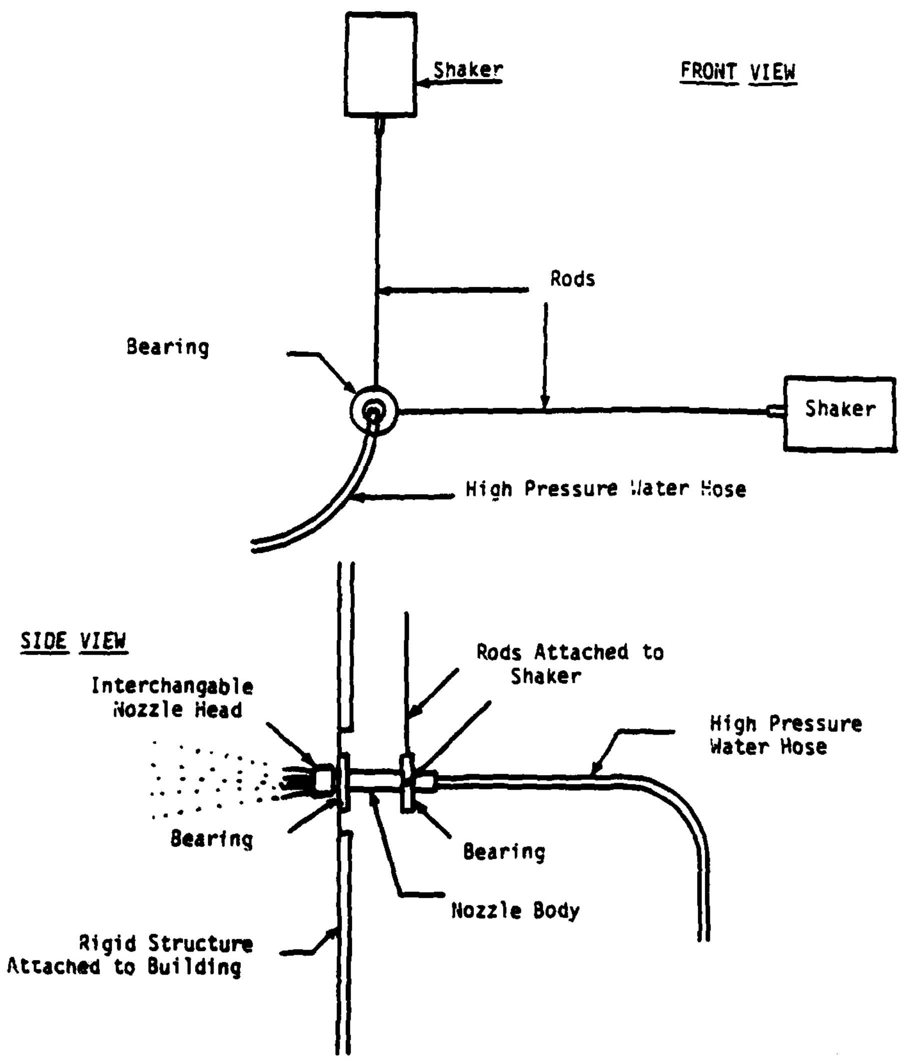


Figure 2. Sketch of Vibrating Nozzle Hardware.

nozzle system to realistically simulate the heavy rain environment at tunnel air speeds from 65 to 125 mph. The nozzle system was specifically designed to achieve the large droplet sizes ($\geq$ 2 mm) that are characteristic of the natural heavy rain environment. The nozzle system also produces the appropriate total water volume for a specified rainrate. The following paragraph gives more details concerning the nozzle system and the logic used in designing it.

Spray Nozzle System

Short duration heavy rain rates that exceed 150 mm/hr occur, on the average, once per year at any given location in the Eastern United States. The volume mean raindrop diameter (i.e., half of the water volume is contained in droplets smaller than the volume mean diameter) of such a rain rate is between 2mm and 4mm. For simulating this intensity rain in a wind tunnel, drag force calculations on large droplets show that the drag force alone is not sufficient to accelerate slow moving droplets to the tunnel velocity in short distances (less than 50 feet) without droplet break-up. Thus, for operations in the UDRI Wind Tunnel, it is apparent the droplets must be injected into the airstream at a velocity near that of the freestream airspeed in the test section. In the UDRI Wind/Rain Tunnel, a high velocity water stream is produced by a water pump that is capable of providing 700 lbs of working pressure at a flow rate of 15 gallons/minute. By varying the water pressure the water nozzle exit velocity can be matched with the test section air velocity. Experimental work by Melene (1967) indicates that a pressure of 700 PSI on a tube nozzle whose length is 50 times its inside diameter should result in a water stream exit velocity of 144 mph at the nozzle tip.

The reason for choosing a vibrating tube nozzle system over a conventional stationary nozzle because of the problem of droplet shattering resulting from high pressure water exiting a conventional nozzle. Spray nozzle literature shows that increasing the pressure in a conventional nozzle results in a

breakup of the waterstream into extremely small droplets. Thus, to achieve a high water speed and large droplets a very large orifice is needed for a conventional nozzle. In fact, literature (Reference 2) indicates that the orifice must be many times larger than the desired volume mean droplet diameter. Unfortunately such a large orifice results in a water volume flow rate that far exceeds that required to simulate heavy rain in the UDRI 3' x 3' tunnel. Table 1 summarizes vibrating tube and conventional nozzle requirements for simulating 250 mm/hour and 500 mm/hour rain rates in the UDRI Wind/Rain Tunnel. With a commercial 30° full jet stationary nozzle, a 7.54 mm orifice is required to produce droplets with volume mean diameter of 3.0 mm. This results in a flow rate of 18.4 gallons/minute. On the other hand, the flowrate required to simulate a 500 mm/hour rain rate at 45 mph airspeed is only 4 gallons/minute. Thus, the conventional spray nozzle supplies over four times the needed amount of water. Applying the same analysis at higher airspeed, the conventional nozzle becomes even more undesirable. In fact, no commercially available nozzles were found that could provide the large droplet sizes at high pressures. On the other hand, results from Melene's tests indicate that generating drops with a tube nozzle using high water pressure results in a drop size greater than the tube orifice diameter, provided the tunnel air speed matches the water speed. To simulate a 500 mm rain rate in the UDRI tunnel a bank of eight tube nozzles is used to provide the proper liquid water content. The eight oscillating tube nozzles, each of diameter 1.4 mm, are positioned to cover all areas of the 3' by 3' test section.

In general, a specified rainrate is simulated with the vibrating tube nozzle system as follows. The volume mean droplet diameter is determined for the specified rainrate. From the volume mean droplet diameter a tube nozzle orifice diameter is

TABLE 1

CONVENTIONAL AND TUBE NOZZLE REQUIREMENTS FOR SIMULATING HEAVY RAIN IN UDRI WIND TUNNEL

| | | | | | TUBE NOZZLE | | | CONVENTIONAL NOZZLE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rain Rate mm/hr | Drop Diameter mm | Airspeed m/hr | Liquid Water gal/min | Water Pressure lbs/in$^2$ | Diameter mm | Flow Rate gal/min | Nozzles No. | Diameter mm | Flow Rate gal/min | Nozzles at 5-1/2 ft | I.D. No. |
| 500<br>15.3 gm/m$^3$ | 3.0 | 45 | 4.0 | 50 | 1.4 | .49 | 8-1/4 | 7.54 | 18.4 | 1/4 | 30150 |
| | | 90 | 8.3 | 275 | 1.4 | 1.00 | 8-1/4 | ---------- | None Available | ---------- | |
| | | 145 | 13.2 | 700 | 1.4 | 1.59 | 8-1/4 | | " | " | |
| | | 175 | 15.6 | 1000 | 1.4 | 1.88 | 8-1/4 | | " | " | |
| 250<br>8.0 gm/m$^3$ | 2.6 | 45 | 2.1 | 50 | 1.1 | .30 | 7 | | " | " | |
| | | 90 | 4.3 | 275 | 1.1 | .62 | 7 | | " | " | |
| | | 145 | 6.9 | 700 | 1.1 | .98 | 7 | | " | " | |
| | | 175 | 8.2 | 1000 | 1.1 | 1.16 | 7 | | " | " | |

chosen that produces these size droplets. The amount of liquid water content to simulate that rainrate is controlled by the number of tubes affixed to the nozzle. The water exit velocity is regulated by choosing the proper water pressure so that water velocity equals the test section airspeed. The spray coverage is regulated by vibrating the nozzles in two directions.

A series of tests has been conducted to determine how well the vibrating tube nozzle system in the UDRI tunnel actually simulates a specified rainfall rate. Particular emphasis in these tests was placed upon generating large droplets that represent rainrates in the range of 250 to 500 mm/hour. A 5D040 nozzle was used to simulate these rainrates. The 5D040 nozzle consists of five tubes of inside diameter .040 inches with tube length 50 times the tube diameter, (two inches). Variation in rainrate is achieved by restricting the spray coverage to a segment of the tunnel test section versus distributing it over the entire 3' x 3' test area. To simulate rainrates in excess of 500 mm/hour a larger droplet size, and thus a larger tube diameter nozzle, is required.

A series of tests were conducted to verify the following characteristics of the nozzle system:

(a) Water exit velocity versus pressure for tube nozzles.

(b) The influence of the differential between air velocity and water velocity on water droplet size. The nozzle system, because of its location in front of the entrance to the tunnel inlet, injects water into a low airspeed region of the tunnel. Thus, a significant velocity differential ΔV, exists between the water stream and the airstream near the nozzle. The effect of this velocity differential in breaking up the water stream into droplets was evaluated.

(c) The shattering of droplets due to vibrating the nozzle system at high frequency.

The following section describes the results of these tests and the conclusions that were reached.

## Test 1 - Water Velocity versus Pressure

The nozzle designated 5D040 was used to establish a relationship between the exit velocity of the water stream at the tip of the nozzle and the water pressure reading at the pump. The exit velocity was deduced from the measurement of the amount of water that was drawn from a 50 gallon storage tank in specified intervals of time. The pressure was varied from 50 psi to 700 psi as shown in Table 2. The derived exit velocities varied from 46.7 mph at 50 psi to 143.7 mph at 700 psi. The test results are compared in Figure 3 with experimental data from Melene (1967). The agreement between both sets of data is excellent and allows confident control of water exit velocity by water pressure.

The 5D040 nozzle was used to study the water stream breakup into various sized drops under a differential in water stream and air stream velocity. The water stream exit velocity was controlled by varying the water pressure as indicated by Figure 3.

## Test 2 - Droplet Formation at a Tunnel Speed of 65 mph

This test series consisted of ejecting the water stream into the tunnel at various water nozzle exit velocities with the test section tunnel speed held constant at 65 mph. The nozzle was held stationary for this test. The purpose of the test was to determine the conditions under which large droplets, in excess of 2 mm diameter, could be generated and maintained in the test section of the tunnel. The water pressure was varied from 50 to 350 psi corresponding to a water exit velocity from 48 to 102 mph at the nozzle tip. A water pressure of 150 psi generated an exit water velocity of 65 mph that matched the freestream air velocity of the tunnel test section. Due to the location of the nozzle in

TABLE 2

WATER PRESSURE VERSUS EXIT VELOCITY
TEST DATA FOR 5D040 NOZZLE

| Water Pressure ($lbs/in^2$) | Time Interval Min. | Gallons Pumped | Flow Rate gal/min | Nozzle Exit Velocity miles/hr |
|---|---|---|---|---|
| 50 | 4.5 | 6.02 | 1.34 | 46.7 |
| 100 | 4.0 | 6.24 | 1.56 | 54.3 |
| 150 | 6.5 | 12.69 | 1.95 | 67.9 |
| 200 | 6.0 | 12.91 | 2.15 | 74.9 |
| 250 | 3.0 | 7.53 | 2.51 | 87.4 |
| 300 | 2.5 | 6.67 | 2.67 | 92.9 |
| 350 | 2.5 | 7.10 | 2.84 | 98.9 |
| 400 | 2.5 | 7.75 | 3.10 | 107.9 |
| 450 | 2.5 | 8.18 | 3.27 | 113.8 |
| 500 | 3.0 | 10.33 | 3.44 | 119.7 |
| 550 | 4.0 | 14.42 | 3.61 | 125.6 |
| 600 | 2.5 | 9.04 | 3.62 | 126.0 |
| 650 | 3.0 | 11.83 | 3.94 | 137.1 |
| 700 | 2.5 | 10.33 | 4.13 | 143.7 |

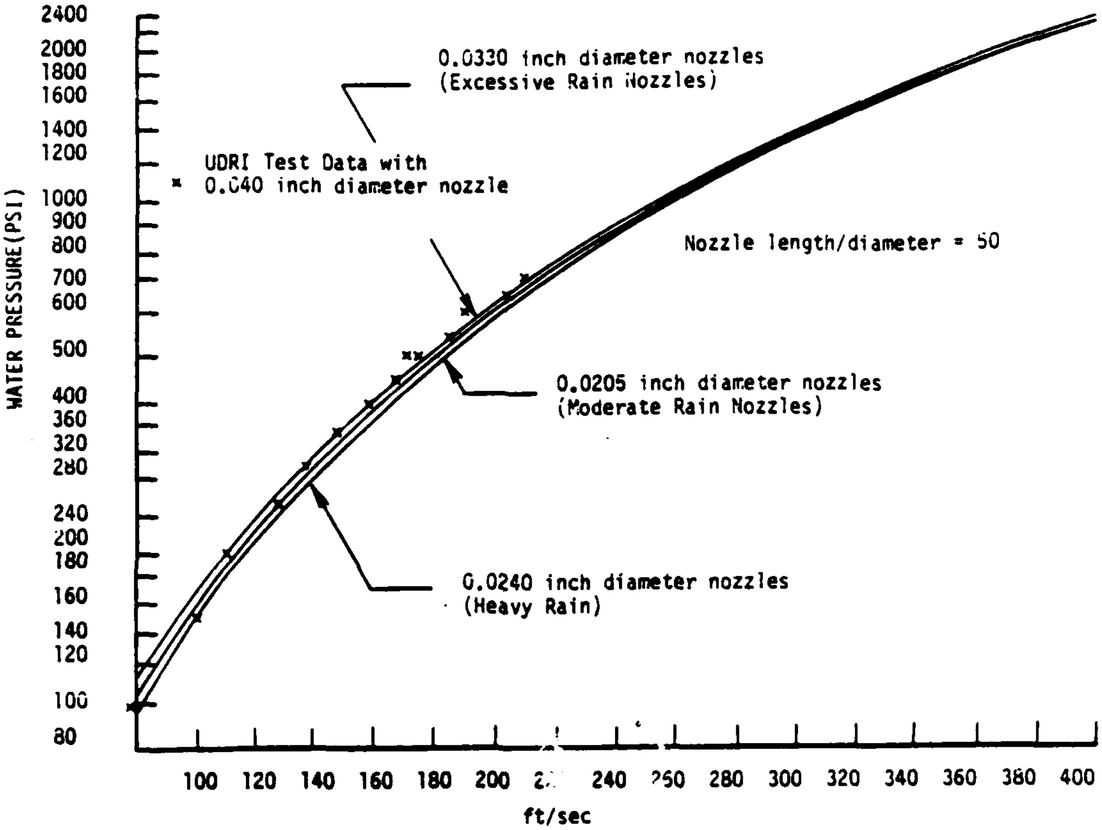


Figure 3. Water Pressure vs. Exit Velocity for Various Nozzles from Melene[1]. X's are UDRI Test Data with .040 inch Diameter Nozzle.

front of the tunnel inlet (a low airspeed region), a large velocity differential existed near the spray nozzle. Table 3 summarizes the test conditons and shows the approximate air velocity at two different locations, 9 inches and 26 inches from the nozzle tip. Still photographs were taken at these locations as well as in the test section of the tunnel. The photographs were taken with a high intensity short duration flash (1/2 microsecond) that effectively resulted in a stop action image. Selected photographs from this series are shown in Figures 4-11 These and other photographs were anlyzed and many interesting observations are noted. In all test cases, the breakup of the water stream into drops occurs in an area 9-14 inch from the nozzle. At lower water pressures where the velocity differential near the nozzle is small, the water stream breaks into 2-3 mm drops without generating a large volume of smaller drops. With increased pressure the water stream shatters into a spectrum of droplet sizes with a large quantity of both small and large droplets being formed. Photographs taken 26 inches downstream from the nozzle easily distinguish the formation of large droplets at a low velocity differential from the generation of a spectrum of drop sizes at a high velocity differential. Consequently, the velocity differential in the first 26 inches from the nozzle is extremely important in determining droplet size distribution. The photos in the test section of the tunnel show that little if any additional breakup of droplets occur between 26 inches and the test section. The test conditions that show large droplets at 26 inches also show the same droplet sizes in the test section. Similarly when shattering occurs, small droplet size distributions occur both at the 26" area and in the test section of the tunnel. In this test series, water stream shattering into smaller (less than 2 mm) droplets began when $\Delta V \approx 56$ mph,(9 inches), and $\Delta V \approx 42$ mph (26 inches). Severe shattering, with droplet sizes less than 1 mm, occurred when $\Delta V \approx 93$ mph (9 inches) and $\Delta V \approx 79$ mph (26 inches).

## TABLE 3

### TEST SERIES AT TUNNEL SPEED OF 65 mph (NO SHAKING OF NOZZLE)

| PRESSURE PSI | NOZZLE EXIT VELOCITY MPH | AIR VELOCITY MPH | | | $\Delta V = V_{water} - V_{air}$ MPH | | | DROP SIZE (FROM PHOTOS) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 9" | 26" | TEST SECTION | 9" | 26" | TEST SECTION | 9" | 26" | TEST SECTION |
| 50 | 48 | 9 | 23 | 65 | 39 | 25 | -17 | Large Drops | 2-3mm | 2-3mm |
| 100 | 54 | 9 | 23 | 65 | 45 | 31 | -11 | Large Drops | 2-3mm | 2-3mm |
| 150 | 65 | 9 | 23 | 65 | 56 | 42 | 0 | No Photos | Many Large | 1-3mm |
| 200 | 76 | 9 | 23 | 65 | 67 | 53 | 11 | No Photos | Globs Of Water | 1-2mm |
| 350 | 102 | 9 | 23 | 65 | 93 | 79 | 37 | Drops Forming | Globs Of Water Shattered In All Size Drops | $\geq$ 1mm |

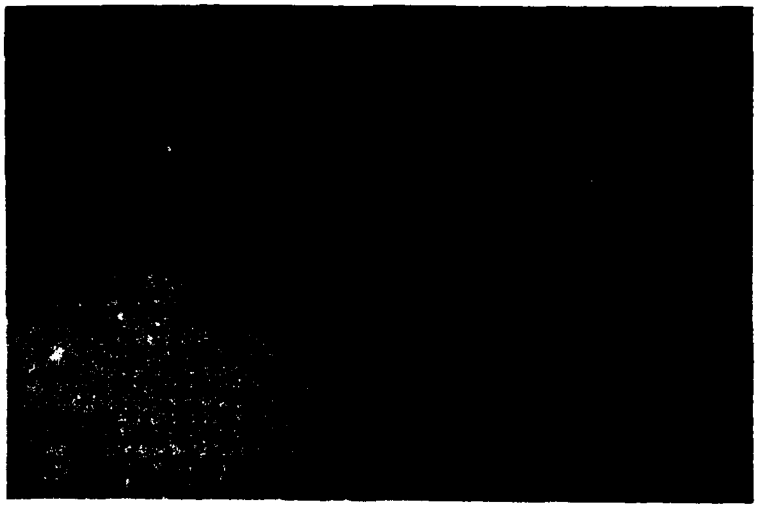

Figure 4 Large Spherical Drops Forming 9" from Nozzle Tip. Water Pressure = 100 PSI, Test Section Airspeed = 65 mph, $\Delta V$ = 56 mph (9 inches).

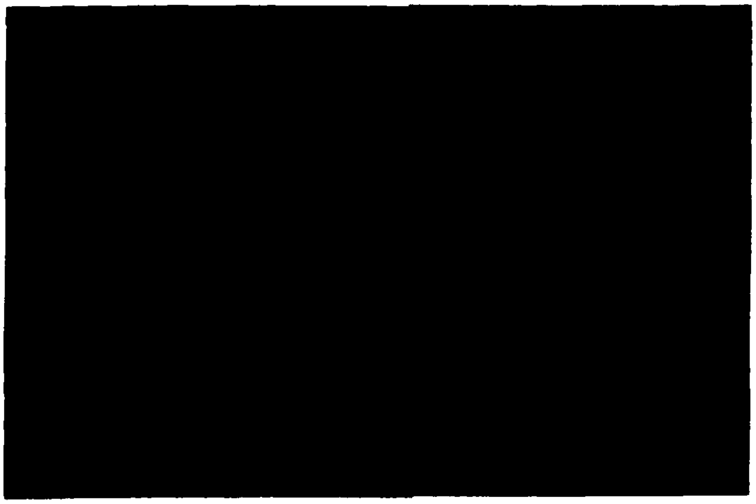

Figure 5 Spherical Drops already formed at 26". Water Pressure = 100 PSI, Test Section Airspeed = 65 mph, $\Delta V$ = 42 mph (26 inches).

Figure 6 Many Large Spherical Drops in Test Section. Water Pressure = 100 PSI, Test Section Airspeed = 65 mph, $\Delta V = 0$ (Test Section).

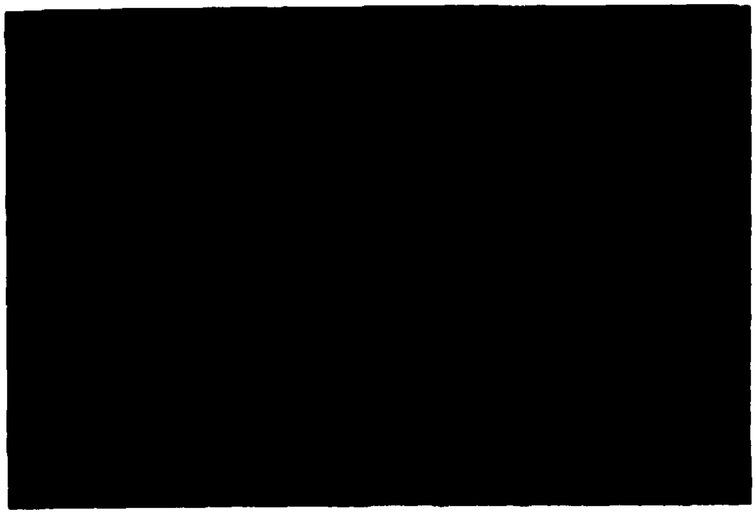

Figure 7 Water Stream Shattering into Spectrum of Drop Sizes at 26" from Nozzle. Water Pressure = 200 PSI., Test Section Airspeed = 78 mph. $\Delta V$ = 48 mph (26 inches).

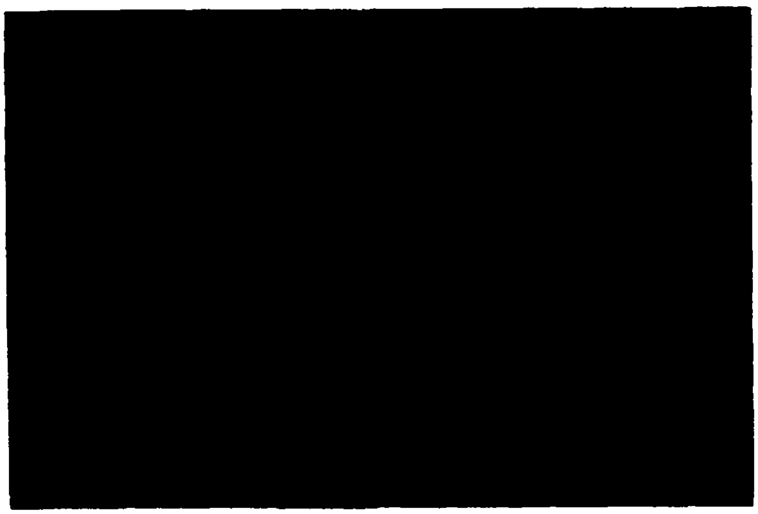

Figure 8 Spectrum of Drop Sizes in Tunnel Test Section. Water Pressure = 200 PSI. Test Section Airspeed = 78 mph. $\Delta V$ = 2 mph (Test Section).

Figure 9 Large Flattened Drops in Test Section. Water Pressure = 100 PSI Test Section Airspeed = 125 mph, $\Delta V$ = -71 mph (Test Section).

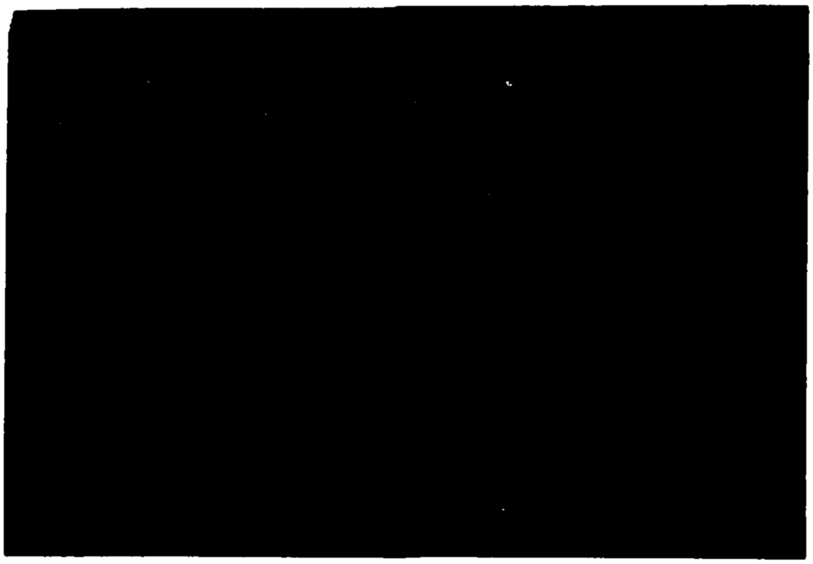

Figure 10 Spectrum of Smaller Drop Sizes in Tunnel Test Section. Water Pressure = 550 PSI, Test Section Airspeed = 125 mph, $\Delta V$ = 4 mph (Test Section).

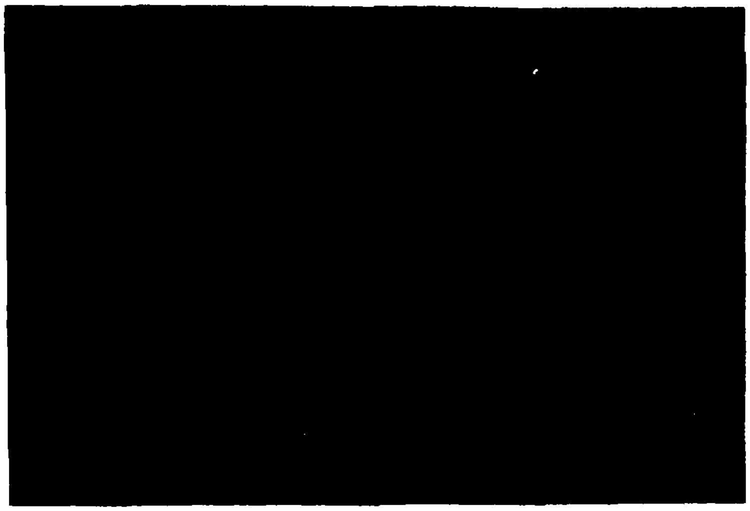

Figure 11 Larger Spherical Drops in Tunnel Test Section with Nozzle Vibrating Horizontally at 10 Hertz. Water Pressure [illegible] Tunnel Airspeed = 65 mph.

## Test 3 - Droplet Formation at a Tunnel Speed of 78 mph

The third test series was an extension of Test Series 2 to a tunnel airspeed of 78 mph. Table 4 summarizes the test conditions. The water nozzle exit velocity was increased to 133 mph by increasing the pressure to 600 psi. Photographs were taken in the test section of the tunnel only. The results are similar to those obtained from the Test 2 Series. At low water velocities large drops were formed and remained large through the test section of the tunnel. Shattering into smaller droplets began to occur at a pressure of 200 psi, which corresponds to $\Delta V \approx 65$ mph (9 inches) and $\Delta V \approx 48$ mph (26 inches). Severe shattering, with droplet sizes less than or equal to 1 mm, occured with 600 psi water pressure. This corresponded to $\Delta V \approx 122$ mph (9 inches) and $\Delta V \approx 105$ mph (26 inches). These $\Delta V$s should be considered the upper limit for severe shattering since no pressure measurements between 350 and 600 psi were made.

## Test 4 - Droplet Formation at a Tunnel Speed of 125 mph

The fourth test series extended the previous test series to a tunnel airspeed of 125 mph. The water pressure was varied from 50 psi to 700 psi, in increments of 50 to 100 psi. This corresponded to a nozzle tip water exit velocity range of 48 to 144 mph. Again the nozzle was held fixed. Photographs were taken only in the test section of the tunnel. Analysis of these photos show that for water pressures between 50 and 200 psi the predominant size of droplets in the test section was 2 to 3 mm diameter. At 200 psi, the velocity differential at 9 inches is $\Delta V \approx 50$ mph and at 26 inches $\Delta V \approx 31$ mph, with the water stream velocity exceeding that of the airstream. In the tunnel test section, however, the airspeed was often considerably larger than the droplet speed. Table 5 shows $\Delta V$ in the test section varying from -77 mph to -49 mph over the 50-200 psi range. Thus at low water pressure, the velocity differential is small positive near

TABLE 4

TEST SERIES AT TUNNEL AIRSPEED OF 78 mph
(NO SHAKING OF NOZZLE)

| PRESSURE PSI | NOZZLE EXIT VELOCITY MPH | AIR VELOCITY MPH | | | $\Delta V = V_{water} - V_{air}$ MPH | | | OBSERVATIONS FROM PHOTOS |
|---|---|---|---|---|---|---|---|---|
| | | 9" | 26" | TEST SECTION | 9" | 26" | TEST SECTION | TEST SECTION |
| 50 | 48 | 11 | 28 | 78 | 37 | 20 | -30 | Large Spherical 2-3mm Drops |
| 100 | 54 | 11 | 28 | 78 | 43 | 26 | -24 | Large Spherical 2-3mm Drops |
| 150 | 65 | 11 | 28 | 78 | 54 | 37 | -13 | Large Spherical 2-3mm Drops |
| 200 | 76 | 11 | 28 | 78 | 65 | 48 | - 2 | Many 2-3mm Drops Some Smaller |
| 350 | 102 | 11 | 28 | 78 | 91 | 74 | 24 | Many Large, Many Small |
| 600 | 133 | 11 | 28 | 78 | 122 | 105 | 55 | Mostly 1mm Drops and Smaller |

TABLE 5

TEST SERIES AT TUNNEL AIRSPEED OF 125 mph
(NO SHAKING OF NOZZLE)

| PRESSURE PSI | NOZZLE EXIT VELOCITY MPH | AIR VELOCITY MPH | | | $\Delta V = V_{water} - V_{air}$ MPH | | | OBSERVATIONS FROM PHOTOS TEST SECTION |
|---|---|---|---|---|---|---|---|---|
| | | 9" | 26" | TEST SECTION | 9" | 26" | TEST SECTION | |
| 50 | 48 | 18 | 45 | 125 | 30 | 3 | -77 | Large Drops Flattened, Many Smaller Drops |
| 100 | 54 | 18 | 45 | 125 | 36 | 9 | -71 | Mostly Large Flattened Drops |
| 150 | 65 | 18 | 45 | 125 | 47 | 20 | -60 | Mostly Large Flattened Drops |
| 200 | 76 | 18 | 45 | 125 | 58 | 31 | -49 | Many Large Flattened Drops Some Smaller Drops |
| 250 | 89 | 18 | 45 | 125 | 71 | 44 | -36 | Many Large (2-3mm) Many Smaller |
| 350 | 102 | 18 | 45 | 125 | 84 | 57 | -23 | Mostly 1-2mm Drops, Some Smaller |
| 450 | 115 | 18 | 45 | 125 | 97 | 70 | -10 | All Sizes Up To 3mm |
| 550 | 129 | 18 | 45 | 125 | 111 | 84 | 4 | All Sizes Up To 3mm |
| 650 | 137 | 18 | 45 | 125 | 119 | 92 | 12 | Mostly 1mm Drops And Smaller |
| 700 | 144 | 18 | 45 | 125 | 126 | 99 | 19 | Mostly 1mm Drops And Smaller |

the nozzle but very large negative in the test section of the tunnel. In the photographs, this large differential in the test section was characterized by flattened droplet shapes. In the most extreme case, with a velocity differential of 77 mph in the test section, the photo indicates that some of the large flattened drops apparently shatter into smaller sizes. However, tests at a smaller velocity differential did not show shattering. For pressures of 100 and 150 psi, with velocity differentials of 71 and 60 mph respectively, the test section photos showed large flattened drops without the presence of a significant number of small drops. These results substantiate the early observation that the shattering and breakup occurs primarily in the area 9 to 26 inches from the nozzle and that once drops have formed, little additional breakup occurs. In this test series, droplet shattering began to occur at a pressure of ≈ 250 psi and severe shattering began at a pressure range of 550 to 650 psi. These transition regimes for a) the initiation of shattering correspond to a $\Delta V \approx 71$ mph (9 inches) and $\Delta V \approx 44$ mph (26 inches) and b) for severe shattering $\Delta V \approx 119$ mph (9 inches) and $\Delta V \approx 92$ mph (26 inches). These numbers, of course, can only be considered approximate.

Test 5 - Effect of Nozzle Shaking on Droplet Breakup

This test series consisted of repeating selected tests from the previous series. All conditions were identical except that in this series the nozzle was vibrated in a horizontal plane at a frequency of 10 Hz. The amplitude of the horizontal oscillation distributed water droplets over nearly the entire 3' horizontal dimension of the tunnel test section. Table 6 summarizes the test conditions for this series. In addition to the water stream breakup due to the instability of a water jet and to shear forces, a force due to the movement of the nozzle back and forth horizontally, was introduced. This series was designed to deter-

TABLE 6

TEST SERIES WITH VIBRATING NOZZLE
(TUNNEL AIRSPEED = 0, 65, 125 mph)

| PRESSURE PSI | NOZZLE EXIT VELOCITY MPH | AIR VELOCITY MPH | | | $\Delta V = V_{water} - V_{air}$ | | | OBSERVATIONS FROM PHOTOS TEST SECTION |
|---|---|---|---|---|---|---|---|---|
| | | 9" | 26" | TEST SECTION | 9" | 26" | TEST SECTION | |
| 50 | 48 | 0 | 0 | 0 | 48 | 48 | 48 | Mostly Large 1-3mm Drops |
| 300 | 93 | 0 | 0 | 0 | 93 | 93 | 93 | Small Drops $\leq$ 1mm |
| 50 | 48 | 9 | 23 | 65 | 37 | 25 | -17 | No Drops Observed |
| 150 | 65 | 9 | 23 | 65 | 56 | 42 | 0 | No Drops Observed |
| 300 | 93 | 9 | 23 | 65 | 84 | 70 | 28 | Large Drops 2-3mm Some Smaller |
| 50 | 48 | 18 | 45 | 125 | 30 | 3 | -77 | No Drops Observed |
| 150 | 65 | 18 | 45 | 125 | 47 | 20 | -60 | No Drops Observed |
| 300 | 93 | 18 | 45 | 125 | 75 | 48 | -32 | Many 1-2 mm Drops, Some Smaller |
| 500 | 122 | 18 | 45 | 125 | 104 | 77 | -3 | No Drops Observed |
| 650 | 137 | 18 | 45 | 125 | 119 | 92 | 12 | No Drops Observed |

mine if the oscillation induced force resulted in further breakup of the drops. Photographs were taken in the test section and compared with the images seen under the same conditions in previous tests without nozzle vibration. The photographs were evaluated to determine if any difference in droplet size could be seen as a result of changing only one variable, the shaking of the nozzle. Unfortunately, usable photographs were not obtained for most of the test configuration. Because of a shallow depth of focus for the camera, droplets could only be observed if the shaking mechanism resulted in droplets being in the observed volume during the short time in which the volume was illuminated by the flash, (1/2 microsecond). If the shaking mechanism resulted in droplets being thrown to a different part of the test section during that time interval, then the photographs were essentially blank. In only a few test cases were there actual observations of a significant number of drops. In comparing these test cases to the previous cases without shaking, no difference in droplet size distributions could be observed due to shaking. Thus, tentatively, it does not appear that shaking has any significant influence on droplet breakup. However, further tests are recommended to verify these results.

## Summary and Conclusions

The vibrating tube nozzle concept is capable of generating large droplet sizes and the proper liquid water content to simulate heavy rain in a wind tunnel at air speeds up to 145 mph. The critical region for droplet size formation is in the area 9 to 26 inches downstream from the nozzle tip. In this region the water jet breaks down either from capillary forces into large droplets (2 - 3 mm) or due to shear forces into a wide spectrum of smaller droplets. Experimental tests indicate that if the velocity difference between the water jet and air stream at 9 inches is less than 50 mph and at 26 inches less than 40 mph,

then large droplets will form whose diameters may often exceed twice the tube diameter. After droplets are formed in this region, further droplet breakup does not occur even if the velocity differential increases to 70 mph. Droplet flattening, however, does occur with a larger velocity differential. The influence of shear forces in shattering of a water jet into smaller sized droplets (< 2 mm) begins after the velocity differential at 9 inches downstream from the nozzle exceeds 50 mph or at 26 inches, 40 mph. At this threshold, moderate droplet shattering occurs. The volume mean droplet diameter under these conditions ranges from 1 to 2 mm. Severe shattering occurs when the velocity differential at 9" exceeds ≈ 110 mph and/or at 26" exceeds ≈ 90 mph. Above this threshold nearly all droplets are 1 mm and smaller. The threshold criteria were generated for water stream breakup with a non-vibrating nozzle of inside diameter .040 inches. If the nozzle is oscillating or if the nozzle tube diameter is somewhat different the results are not expected to differ significantly. Limited experimental tests with vibrating nozzles suggested no further droplet breakup could be attributed to oscillating the nozzle. Further tests, however, are recommended to substantiate this conclusion. These tests were conducted on a nozzle designed to simulate rain rates between 250 and 500 mm/hour. Additional experimentation is recommended to verify the above conclusions when simulating rainrates in different ranges.

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